A Study of Hurricane Tracks for Forecasting Purposes[1]

By

José A. Colón

University of Chicago

Introduction

The prediction of the motion of tropical cyclones continues to be one of the major problems of forecasting in tropical and subtropical latitudes. One main difficulty lies in the fact that many of the techniques and aids suggested through the years require more extensive data than ordinarily available to the forecaster. Two simple approaches which do not depend on a great amount of synoptic information are those based on climatology and persistence. These two approaches are the primary concern of this paper. Under the former approach, insight into the motion of the storm is given by the behavior of past storms in the same region and in the same month. In the latter, prediction is based on the behavior of the same storm during its previous history; usually, the preceding 24-hour period is considered.

Although their reliability is at times questioned, these approaches are used frequently at forecasting centers. Many times they are the only available tool in oceanic regions where data are inadequate for a confident analysis of the tropospheric flow in the area of the storm. Even when a reliable upper-air analysis is available, a careful study of the previous history of a storm should precede any forecast. The previous track gives the best indication of what the steering current has been and, thus, will help in deducing the future one.

Since, for some time to come, hurricane forecasters will have to deal with inadequate data, we should attempt to extract from past experience everything which leads toward a more efficient and confident application of the statistics. The present study represents such an attempt. The climatological data on hurricane tracks are reduced to a form which permits a quantitative estimate of the probability of success of persistence forecasting.

Data and Method of Analysis

The data used consist of tracks of tropical cyclones of all intensities charted in the Caribbean Sea, the Gulf of Mexico, and adjacent regions of the Atlantic ocean during the period 1887-1950. In these 64 years, 473 storms were observed. Cyclone tracks for the period 1887-1932 are given in Mitchell's publications [1, 2]. After 1932, the tracks appear in annual summaries of the Monthly Weather Review.

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[1] This is a report on research conducted under contracts between the Office of Naval Research and the University of Chicago.

The region from 10°N to 35°N and from 40°W to 100°W was divided into 5° latitude-longitude squares for the computations. In each square, a spot approximately in the center of each storm path was taken as the observation point, and the direction and speed of motion in the preceding and following 24-hour periods were tabulated. Each storm supplied one observation regardless of the time it took to move through the square. The numbers in the inner circles in fig. 5 indicate the number of storms observed in each square during each month of the hurricane season, June through November, for the entire 64 years.

Frequency of Storms

Table I gives the average monthly frequency of storms on a 10-year basis.

Table I

Average Monthly Frequency of Tropical Cyclones of All Intensities During the Period 1887-1950, Reduced to 10-Year Basis

	May	June	July	Aug	Sept	Oct	Nov	Total
Frequency	1	4	5	16	24	19	4	74
Percentage Frequency	1	6	7	22	32	26	6	100

Annual frequencies: The average annual frequency per 10 years is 74. About 80% of this total occurs during the three-month period, August to October. The frequency in individual years varied from a minimum of one recorded in 1890 to a maximum of 21 in 1933. Low frequencies of two storms per season have been observed several times, most recently in 1929 and 1930. This constitutes an extreme low of activity during a two-year period. On account of the variability of storm frequency, seasons with storm totals below the mean occur more often than active seasons. This is illustrated in fig. 1, which shows that 50% of the total number of storms occurred in only 30% of the number of seasons. Also, 40% of the seasons account for only 20% of the total frequency of storms.

A graph of seasonal frequency against time shows great variability from one season to the next. The product-moment correlation coefficient for a one-year lag is only 0.19. However, a graph of successive five-year total reveals a very interesting feature (fig. 2). The correlation coefficient for successive five-year totals is 0.46, a relatively high value. Above average values were observed during the period 1886-95, followed by below average values until 1930. A second period of high activity started in 1931 and has continued to the end of the record included in this study. This distribution is not an accidental result of the selection if intervals. During the period from 1910-1930, the seasonal storm frequency was below average in 16 of the 20 years. Since 1931, frequencies below average have been observed only four times.

Fig. 2 suggests a search for periodicities and correlations with slowly varying parameters, such as sunspots. Several attempts at such correlation have been tried but proved unsuccessful.

Monthly frequencies: Fig. 3 contains isolines of total monthly storm frequency for the 64-year period analyzed. These lines indicate how often a storm has passed through each 5° latitude-longitude square. Comparison of the frequency in any square with the total number of storms observed during the month gives information which could be used in risk determinations. For example, the square extending from 25°N to 30°N and from 80°W to 85°W, which comprises most of Florida, has had nine storms in June during the 64 years. In the same period a total of 27 June storms was charted for the whole hurricane region. This means that one-third of all storms passed through this square, and thus, either affected or endangered Florida (probability 0.33).

The probability of storm occurrence in a given month is indicated by the ratio of the number of months with storms divided by the total number of months--64 in our case. Table II shows the probability of storm occurrence for each month in three groups: One or more storms a month, two or more, and three or more. A total of 64 years is perhaps insufficient to obtain completely stable probabilities, but is the best that can be offered. As would be expected, the probability is high from August through October. In September it is almost unity. The probability that more than one storm will occur is also great during this latter month. For instance, the occurrence of three storms in September is more likely than that of one storm in June, July, and November.

Table II

Probabilities of Storm Occurrences per Month

	May	June	July	Aug	Sept	Oct	Nov
At least one storm	0.09	0.34	0.39	0.75	0.92	0.83	0.36
Two or more storms	0.02	0.06	0.11	0.52	0.72	0.59	0.03
Three or more storms	0	0.02	0.03	0.19	0.42	0.34	0.03

From the previous analysis the probability is 0.33 that a June storm will endanger Florida. Table II shows that the probability of a storm occurrence in June is 0.34. We can ask, then, the following question: What is the probability of a storm endangering Florida in June? The answer is given by the product $(0.33) \times (0.34) = 0.11$. Accordingly, it is very likely that a June storm is observed once every three years in the long-term mean; furthermore, that one of every three June storms will affect Florida. Therefore, the mean probability of Florida being endangered by a storm in June is about one ninth; that is, on the average once in nine years.

Table III shows the results of this type of analysis for all months of the hurricane season. Storms in June and October are most likely to affect Florida.

The latter month is most dangerous because of its greater frequency of storms.

Table III

Probabilities of Storms Endangering Florida

	June	July	Aug	Sept	Oct	Nov
From an existing storm	0.33	0.21	0.15	0.23	0.29	0.11
During the month	0.11	0.08	0.11	0.19	0.24	0.04

Fig. 3 can be used to obtain a rough idea of the total number of days with hurricanes. A speed of motion averaging near 15 mph would take a storm from one square to the next in 24 hours. This value is not far from the actual mean speed. Therefore, each observation in a square on the average represents a hurricane-day. The sum of the values in all squares gives the total number of hurricane-days for the region during the entire period. This total divided by 64 (total number of years) gives the average number of hurricane-days per month. The result of this computation is shown in Table IV. A check from storm tracks for the period 1887-1932 has verified the general accuracy of this table.

In addition to general information such as might be used in calculating the average contribution of hurricanes to the atmospheric heat balance, the Table IV can be used to furnish various types of specific information. Given, for instance, a hurricane forecast center which has to predict for the whole area, the staff must be prepared to take care of an average of 16 days in September with a hurricane on the charts. If incipient situations which do not develop are added, it is readily seen that a quiet day in September would be rare for the center. If responsibility for the whole area is divided among several centers, the specific responsibility of each one can be computed in a similar manner from fig. 3.

The number of hurricane-days divided by the mean number of storms per month (Table I) gives a value of slightly over six days for the average life span of a storm south of latitude 35°.

Table IV

Average Number of Hurricane Days per Month

June	July	Aug	Sept	Oct	Nov	Season
2	3	10	16	12	3	46

Regions of Formation

It is difficult to treat the formation of storms quantitatively. Usually, the beginning of a track marks the point where or when high winds begin to be observed. In most cases, this is not the point of first formation. Generally, the initial disturbance has existed and moved for some time prior to intensification. As is common east of the Lesser Antilles, disturbances of storm intensity may exist for a few days before they arrive in the network of observing stations. This problem was most serious during the first part of the period because of scarce data.

Fig. 4 shows the regions of formation as indicated by the initial point of the published storm tracks. In general the charts corroborate previous statements that there are four especially active regions of storm development: the Atlantic east of the Lesser Antilles, the western Caribbean Sea, the Gulf of Mexico, and the Atlantic east and southeast of Florida. The last three regions adjoin geographically and may be combined for some statistical purposes. Table V gives the monthly storm totals east and west of 70°W, a longitude which divides the storm formation in equal halves. August and September are most active in the east, but formation is still appreciable in October. In the west the percent contribution of early and late season storms is much greater than in the east, especially during May-June.

Graphs of seasonal frequency against time for each region using successive five-year totals are presented in fig. 2. The long-range fluctuation evident for the total number of storms is well followed by the eastern storms, but poorly by those in the west. Thus variations in the east have mainly determined the long-period trend. The correlation between the curves for both regions is small (correlation coefficient 0.05). Thus an active season in the eastern region is not necessarily accompanied by high-storm frequency in the west.

One of the most interesting observations in hurricane work is the appearance of what may be called storm "clusters." These are groups of usually two or three storms appearing in succession at intervals of a few days and which seem to have formed in the same location. One of the most clear-cut examples occurred in the 1951 season when three hurricanes moved into the western Atlantic in succession on September 2, 3, and 5.

Table V

Frequency of Storms in the Eastern Atlantic and in the Western Caribbean and Gulf per 10 Years

	May	June	July	Aug	Sept	Oct	Nov	Total
Formation east of 70°W long.	0	0	2	12	14	7	2	37
Formation west of 70°W long.	1	4	3	4	10	12	2	36

In an attempt to investigate this feature, the dates of appearance of all storms from 1883-1950 were investigated in search of clusters. A total of 59 clear-cut cases was discovered. The majority of these consisted of storm pairs. However, there were 11 groups of three storms and one group of four storms.

The frequency of clusters was highest in September (38%), August (28%), and October (21%). If the data on clusters are combined in five-year totals as done for all storms in fig. 2, a similar curve results. Frequencies were below average up to 1930, then above average. This suggests that high-hurricane frequencies are partly produced by storm clusters.

Of the 59 cases, 41 or 70% occurred in the east indicating a definite preference for clusters in the Cape Verde group of storms.

Motion of Storms

Preparation of average hurricane tracks has been undertaken many times. Outstanding is the work of C. L. Mitchell [1] who presented a set of monthly charts giving the resultant directions of motion by $2\frac{1}{2}°$ latitude-longitude squares. Even with an accumulation of 26 more years of data, an increase of 100 percent in the amount of factual information, we do not feel that these charts can be improved greatly.

In our study of the motion of storms, direction and speed have been treated separately. The directions of motion were tabulated in each 5° square using $22\frac{1}{2}°$ sectors centered at W, WNW, NW, etc., (16 cardinal points). The interval of $22\frac{1}{2}°$ was chosen because it was not so large that the results would become useless but large enough for the samples to be significant. From the tabulation, percentage frequencies of direction of motion were computed (fig. 5).

Inspection of the charts immediately shows the modal direction of motion in each square. The significance of the mode is directly available since the length of the arrows gives the percent frequency, also the probability of storm displacement in the modal and other directions. The reliability of fig. 5 is affected only by the magnitude of the samples. These are relatively great in August, September, and October. In June, July, and November, the number of observations is small, but the patterns in these months still are fairly consistent.

In forecasting, fig. 5 has most value in the early stages following detection of a storm. In the absence of other information, it is logical to predict a track along the modal direction. Fig. 5 also tells what direction of motion should not be predicted. In August, for instance, no storm of record in the area south of 25° and east of Florida has moved east of north or south of west. It would be quite illogical to predict such an abnormal path without most cogent reasons.

The confidence in a prediction of a modal track can be estimated from the percentage frequencies of the modes. These are shown separately in fig. 6. We note maxima in the lowest and highest latitudes, with an intermediate axis of minimum frequency situated mostly between 20°-30°N. In some areas, notably the Gulf of Mexico, one can hardly speak of a mode. Weak double or triple modes are found in several squares. Here, fig. 6 is without usefulness. The statistics reflect the large variability of the synoptic weather pattern over the Gulf region. The mean trough aloft, which lies over the Gulf in summer, and the subtropical ridge line oscillate considerably. Since the motion of storms is largely determined by the flow patterns aloft, the lack of a pronounced modal direction in the Gulf area is understandable.

The seasonal changes of the latitude of the subtropical high also are indicated in fig. 6 since the position of the axes of minimum modal frequency correspond in parts of the area to the position of the ridge line at 700-500 mb. The monthly shift of the subtropical ridge follows a regular course (fig. 7) [4]. It lies near 23°N in June, moves northward in July and August, then southward until November.

The minimum axes of fig. 6 undergo similar displacements.

The relation of the subtropical ridge to the storm movement becomes even plainer if we plot (1) lines connecting squares with a modal direction of 360° in each month (fig. 8), and (2) lines connecting squares with maximum frequency of recurvatures (fig. 9). For the latter purpose the westernmost point in the track of a recurving storm was considered as the point of recurvature.

The patterns of figs. 8 and 9 are fairly similar. By and large the axes shift in accord with fig. 7. But we also note considerable irregularities. Presumably the axes of figs. 8-9 reflect the position of the subtropical ridge on days when a recurvature took place, while the means of fig. 7 are for all days. Comparing figs. 7-9 quantitatively on this basis, we find that the subtropical ridge lies on the average 2° latitude farther north on days with recurvature than in the monthly mean.

Speed of Motion

The median values of the speed of motion in each square are shown in fig. 10. An axis of minimum speed lies roughly between 20°-30°N with higher speed to the north and south. In the southern belt, below 20°N, the average speed is 14-16 mph. North of 25°-30°, we observe 14-16 mph during June, July, and August, increasing to over 20 mph in September, October, and November. This increase coincides with the southward shift of the latitude of recurvature and is due to the well-known fact that storms usually speed up considerably on the northeast track after recurvature.

Mean deviations from the values in fig. 10 were computed and analyzed. Motion is fairly constant in the belt of 10°-20°N and in the Gulf of Mexico. Mean deviations are of the order of two to four mph during the whole season. Variability is much greater in the north as the mean deviation increases from four mph in June and July to well above six mph in September, October, and November.

Persistence Computations

One of the main objectives of this study was to determine the probability of success of linear extrapolation. The results presented here are based on persistence of direction. In each square the change in direction of motion between two successive 24-hour periods was tabulated. Looking downstream, the change was considered positive if the storm moved to the right of its previous path, and negative if it moved to the left. For example, if a storm moved in the direction 300° in the initial 24-hour period and 320° in the subsequent period, the angle of change was recorded as +20°. A storm track was considered persistent when the change was within ±10°.

From the tabulated data, the percentage frequency of persistent storms was calculated in each square for each month. Fig. 11 shows the results, which can be interpreted as giving the probability of success of straight line extrapolation. In using fig. 11, it should again be noted that the charts for June, July, and November are based on very limited data.

In general, the probability of success is large in the southernmost belt, but decrease farther north and west. The results are very encouraging in the eastern

Caribbean Sea during the period of greatest danger, July to September, where the chances of persistence are around 80 percent over an extensive area. This represents as large a confidence as can be put on any other forecasting method, a happy outcome for an area in which, due to lack of adequate upper-air data, climatology and persistence serve as important tools of prediction.

In the Gulf of Mexico and adjacent regions persistence is a poor indicator of future storm tracks. In this region, however, upper-air data are more plentiful so that forecasters can rely to a greater extent on other forecasting techniques.

Additional persistance computations were tried for subgroups of the samples. The persistency of storms moving in a direction 270°-300° was compared with that of storms moving between 300°-330° and 330°-360°. The results as far as regional distribution is concerned did not differ significantly from those indicated in fig. 11. There was, however, a significant tendency for storms moving on west to west-northwest tracks to be more persistent than those moving on more northerly tracks. This particular computation was tried only for the month of August.

Computations were made also with respect to speed of motion. Again, the regional distribution did not change, but there was a noticeable tendency for fast moving stoms to be most persistent. This statistical result no doubt is due to the fact that a given acceleration normal to the previous path will produce a smaller change in the direction of motion if the speed is large than if it is small.

Deviations from persistence were also investigated. Most often storms curved to the right. In some regions, particularly over the western Gulf of Mexico changes to the left also were numerous. In the north the frequency of nonpersistent storms exceeds that of persistent storms. The angle of change in the direction of motion of the nonpersistent storms was tabulated and the median of the distribution determined separately for the positive and negative turnings. This median value was then plotted for each square (fig. 12). Reasonable patterns were obtained for all months. In the south the angle of change is smallest. A belt of maximum change lies close to the subtropical ridge line. Values decrease again farther north. The relation of the axes of maximum turning to figs. 6-9 requires no elaboration.

Fig. 11 applies only to straight-line persistence. Other types of persistence can be defined. For instance, one can ask the question to what extent curving storms maintain the same path curvature. This computation would involve higher order derivatives. In view of the uncertainties even in the best storm tracks, no further work was attempted.

<u>Summary</u>

A study of the climatology of formation and motion of tropical storms in the Caribbean area during the period 1887-1950 has verified some known facts and has also shown some results not specifically contained in previous works.

1. The number of hurricanes varies greatly from one year to the next. However, if five-year totals are used, a more uniform time series appears which suggests long-period fluctuations. Above average frequencies were observed between 1887-95; below average afterwards up to 1930, then above average again beginning in 1931. This variation is produced mainly by storms forming east of 70°W. Very little correlation exists between the frequencies of formation east and west of this longitude.

2. The frequency distribution of the number of storms per season shows that the number of seasons with very low activity exceed that with high frequencies. Because of this skewness in the distribution about 40% of the total number of seasons contribute only 20% of the number of storms whereas 30% of the number of seasons account for 50% of the number of storms.

3. An example of risk computations for Florida shows that October is the most dangerous month in this area. Tables I and II and fig. 5 make possible similar computations anywhere within the area covered.

4. An estimate of the average number of hurricane days per month varies from a minimum of two in June to a maximum of 16 in September. The average duration of storms south of 35°N is around six days.

5. The formation of storms occurs very frequently in the form of groups or "clusters" of two or more storms which appear in quick succession in the same region. These "clusters" are most frequent in August, September, and October. They occur predominately among the storms moving from the eastern Atlantic.

6. The climatological data on the motion of storms are presented in figs. 5-6 in a form that permits a quick determination of the probability of motion along each direction at each 5°latitude-longitude square. The regions where the climatological approach in forecasting has the greatest probability of success are delineated.

7. The median speed of motion is highest in the belts 10°-20° and north of 30°N, slowest between 20° and 30°N, especially in the Gulf of Mexico. Deviations from the median are fairly small in the south and large in the north.

8. The probability of success of straight-line persistence is studied. The confidence of a persistence forecast at any locality in any month can be read from fig. 11. Regions are delineated where persistence has at least the same chance of success as other forecasting techniques. Nonpersistent storms move predominantly to the right of their previous path. The median angle of turning is 20°-30° in most areas with smallest angles in the lowest latitudes and largest angles in the vicinity of the subtropical ridge.

__Acknowledgements__

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References

[1] Mitchell, C. L., 1924: West Indian Hurricanes and Other Tropical Cyclones of the North Atlantic Ocean, Mon. Wea. Rev., Suppl. No. 24, 47 pp.

[2] Mitchell, C. L., 1932: West Indian Hurricanes and Other Tropical Cyclones of the North Atlantic Ocean, Mon. Wea. Rev., 60, p. 253.

[3] Tannehill, I. R., 1942: Hurricanes. Princeton: Princeton University Press, 265 pp.

[4] U. S. Weather Bureau, 1952: Normal Weather Charts for the Northern Hemisphere, Technical Paper #21, 74 pp.

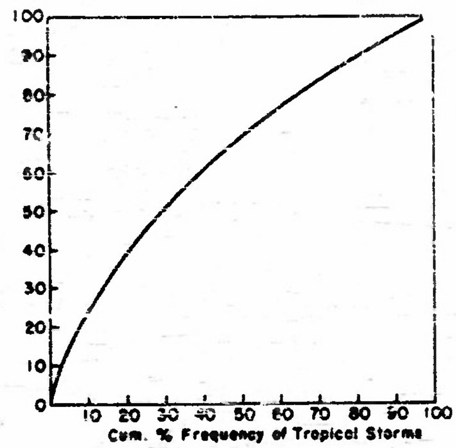


Fig. 1: Accumulative percent frequency distribution of the number of tropical storms against accumulative percent of years studied.

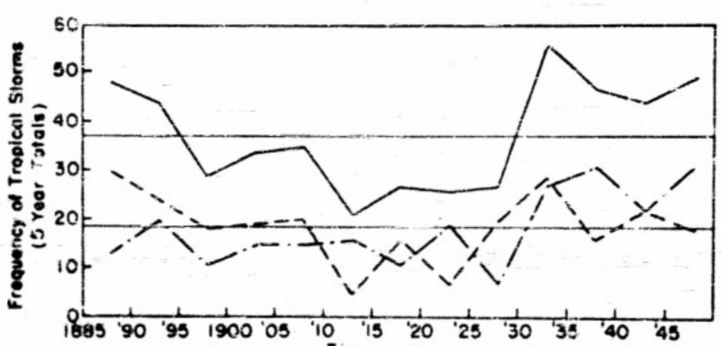


Fig. 2: Frequency of tropical cyclones of all intensities in the Caribbean-Atlantic area by five-year sums from 1886-1950. Solid curve indicates total frequency; dashed curve frequency of storms formed east of 70°W, dot-dashed curve storms formed west of 70°W. Thin horizontal solid lines indicate the averages on a five-year basis.

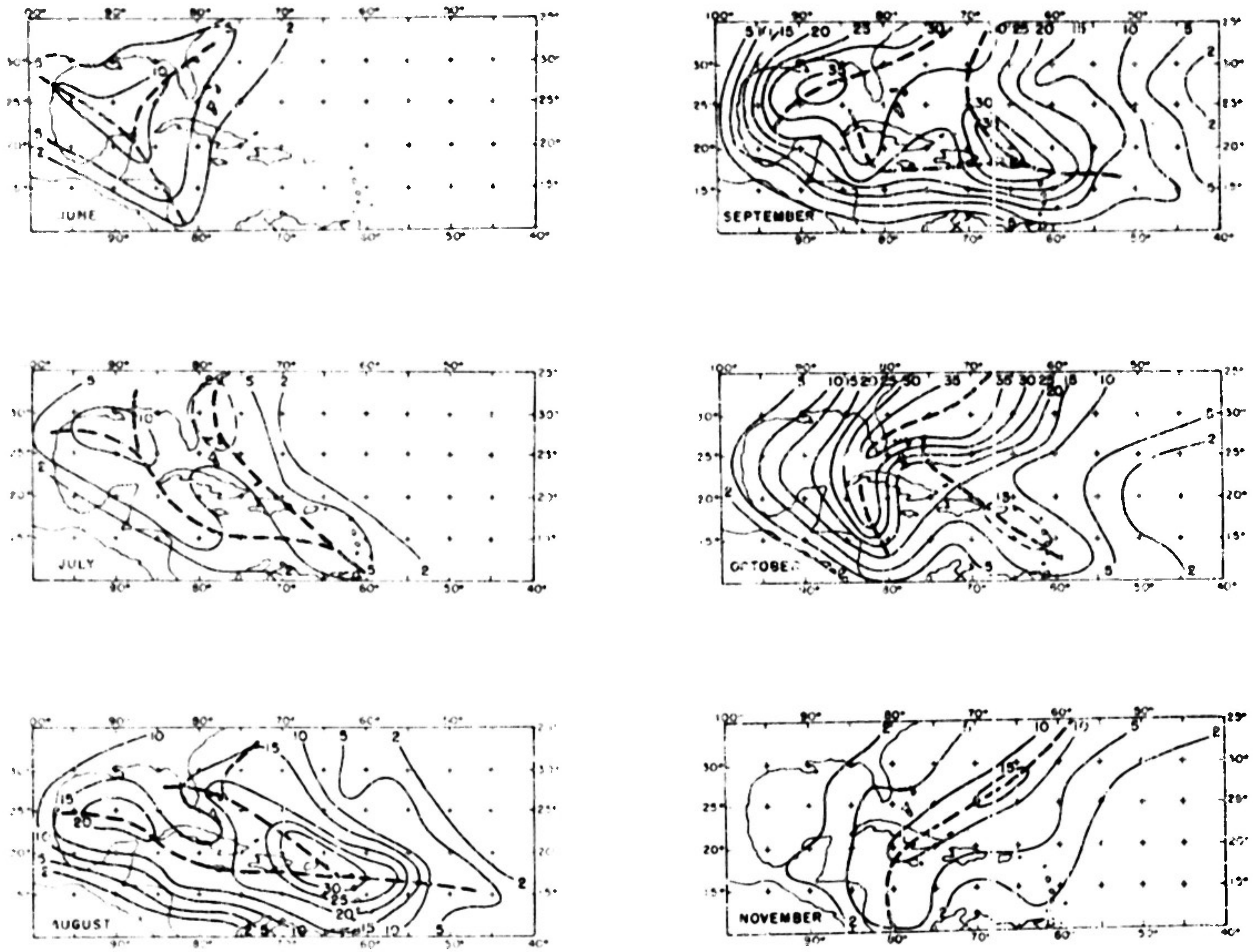


Fig. 3: Total frequency of tropical cyclones crossing each 5° latitude-longitude square during the 64-year period, 1887-1950. Heavy dashed lines indicate axes of maximum values.

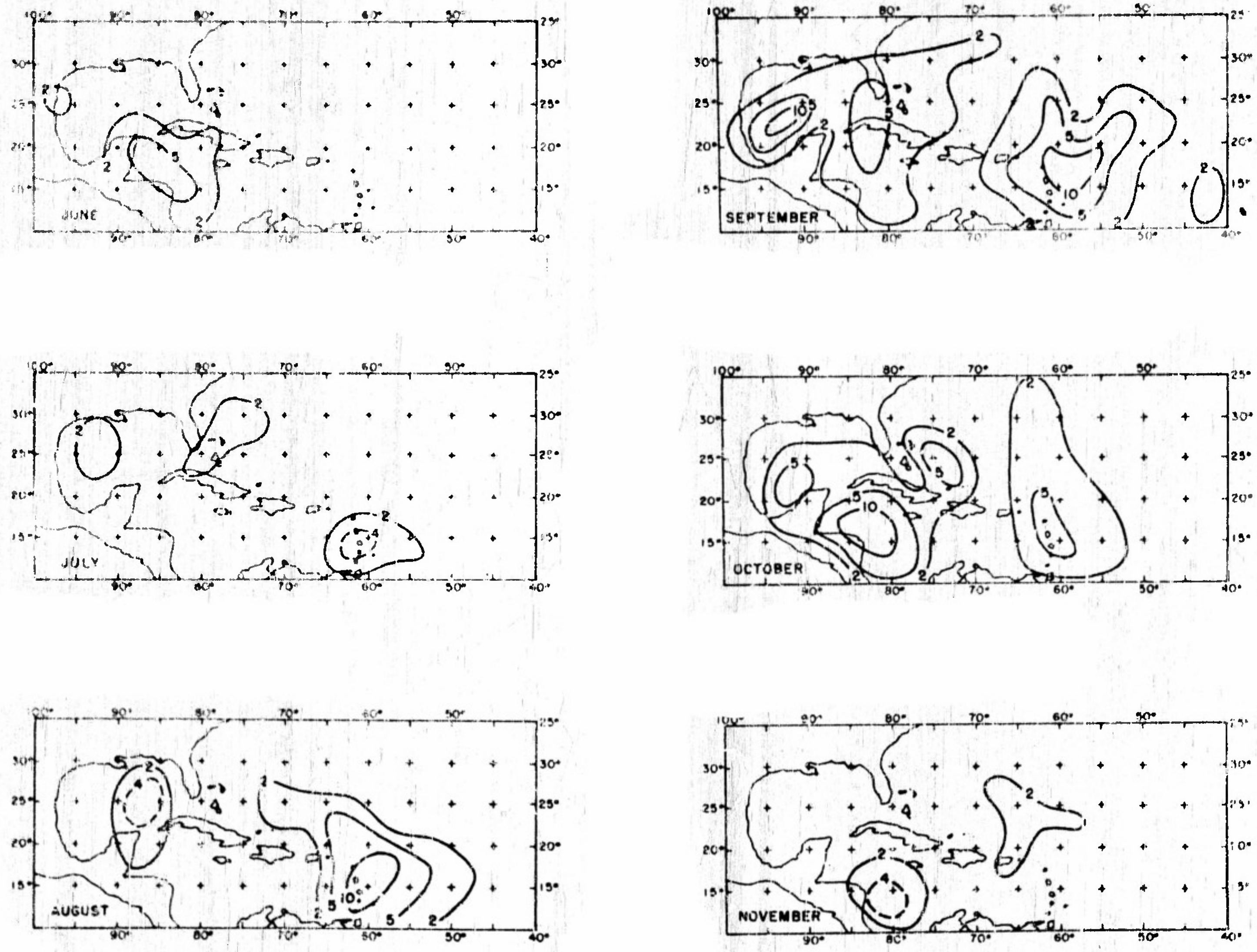


Fig. 4: Total frequency of tropical cyclones with track starting at each 5° square during the period 1887-1950.

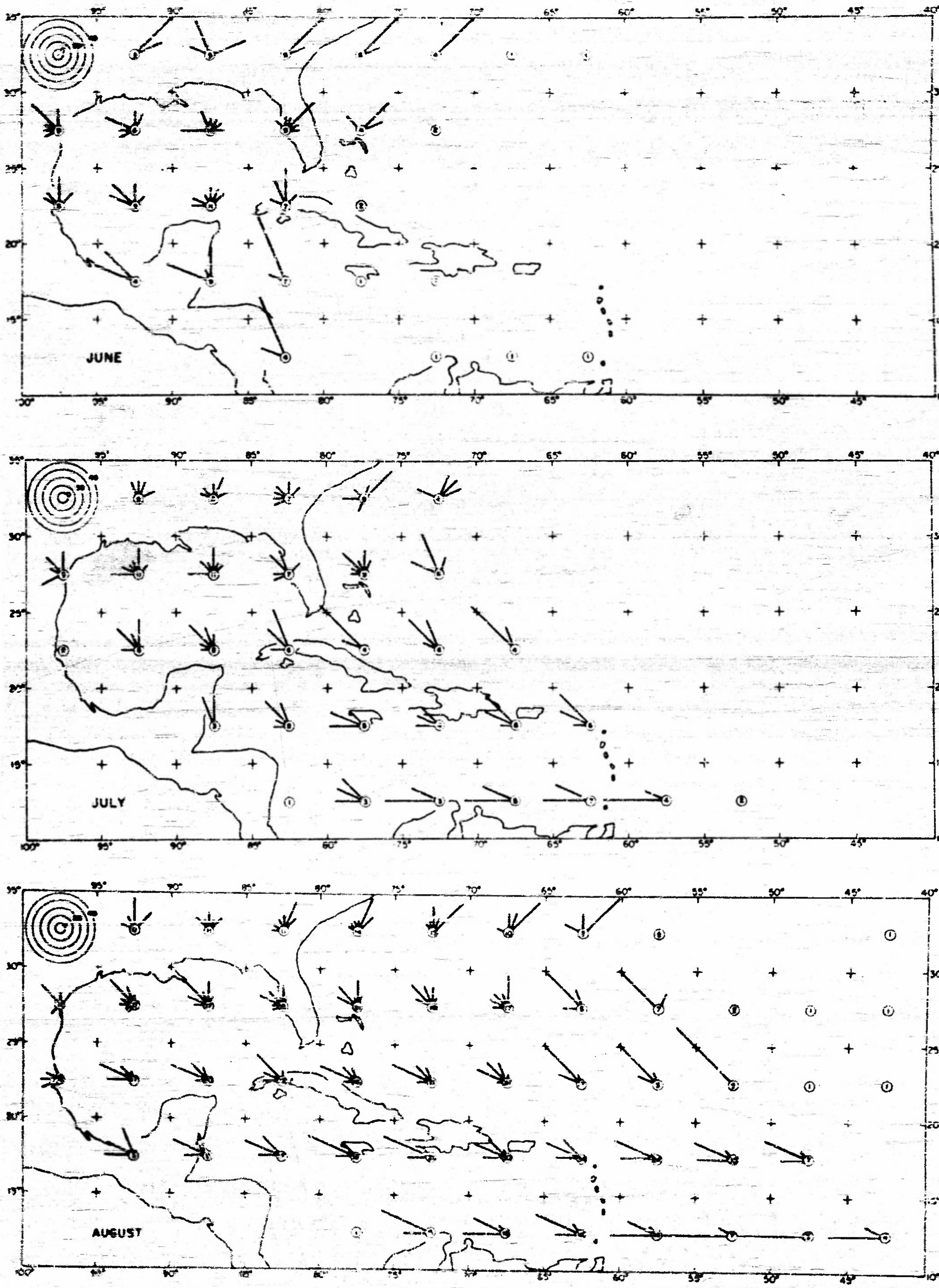
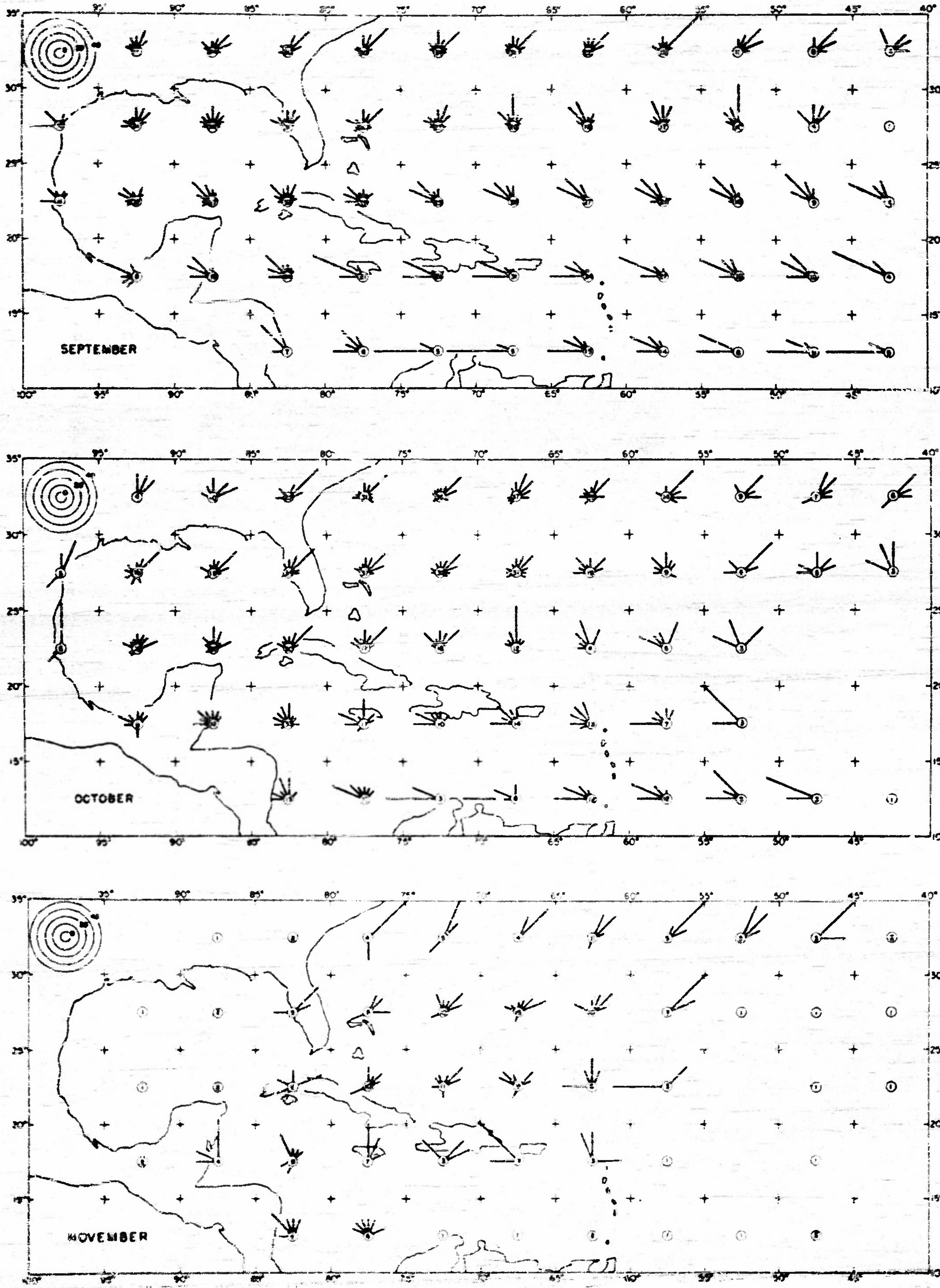


Fig. 5: Percentage frequency distribution of the direction of motion of tropical observed in each square. The length of each vector gives the percentage frequency of upper left-hand corner.



cyclones by 5° squares. The number in the inner circle represents the number of storms storms moving in a 120° sector centered at that direction. The scale is shown in the

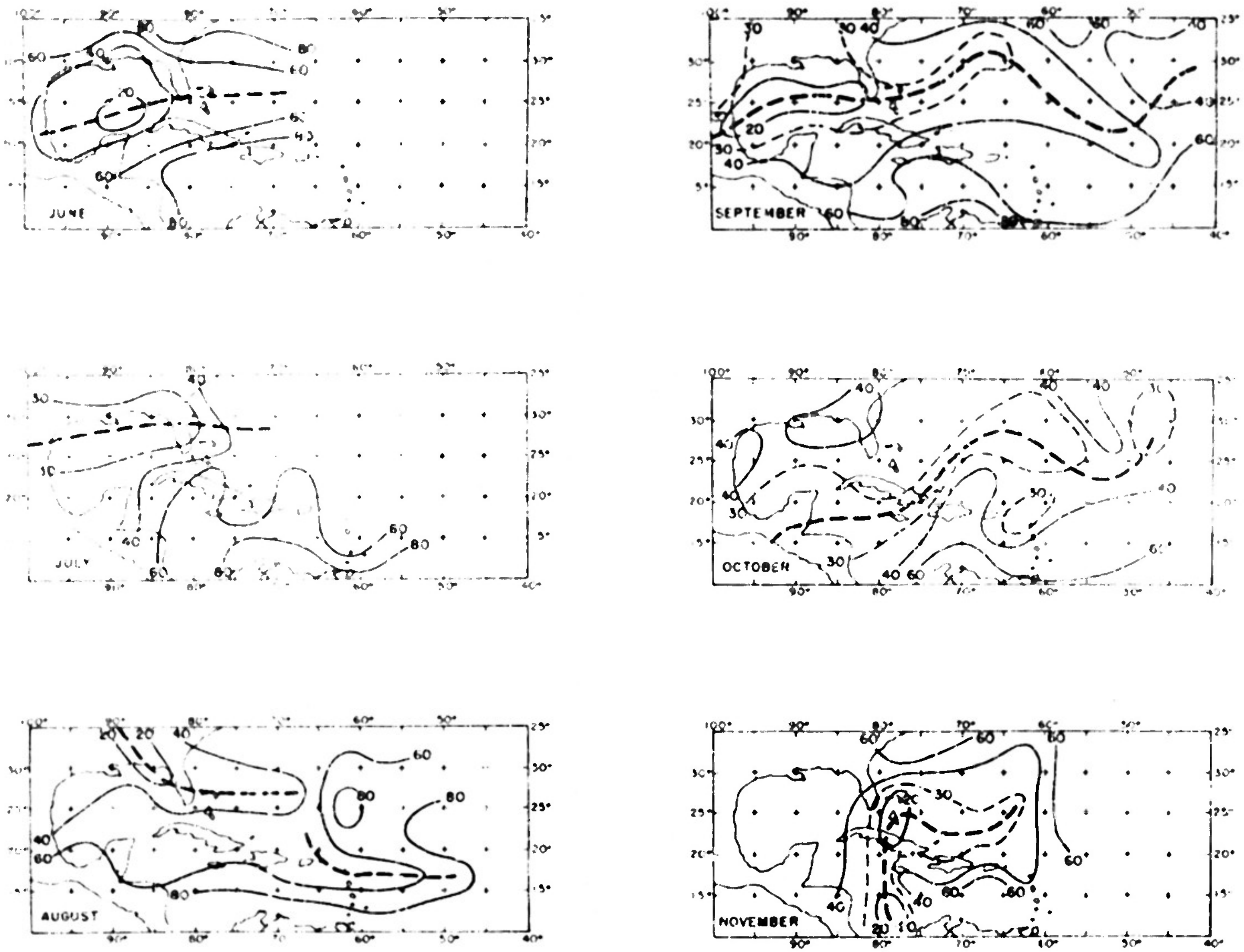


Fig. 6: Percentage frequency of motion along the modal direction. Heavy dashed lines represent axes of minimum frequency.

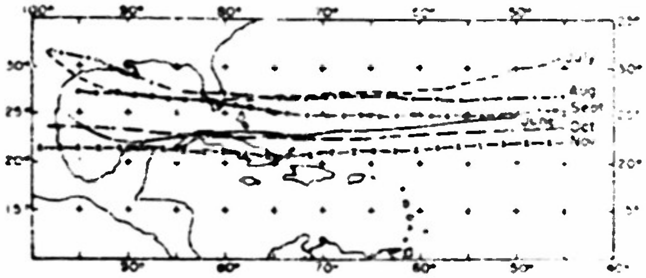


Fig. 7: Mean Monthly position of the latitude of the subtropical ridge line at 700 mb [4].

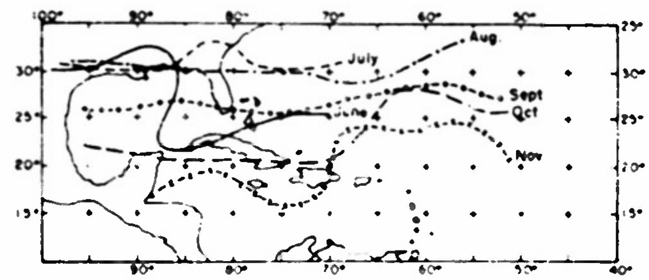


Fig. 8: Lines showing latitude of modal direction of motion of 360° in each month. South of these lines storms move mainly with a component toward west, to their north toward east.

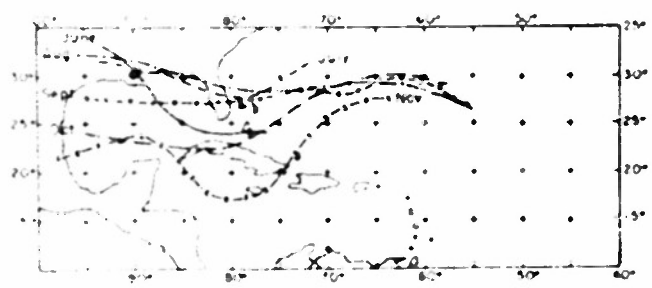


Fig. 9: Lines showing latitude of modal occurrence of recurvature in each month.

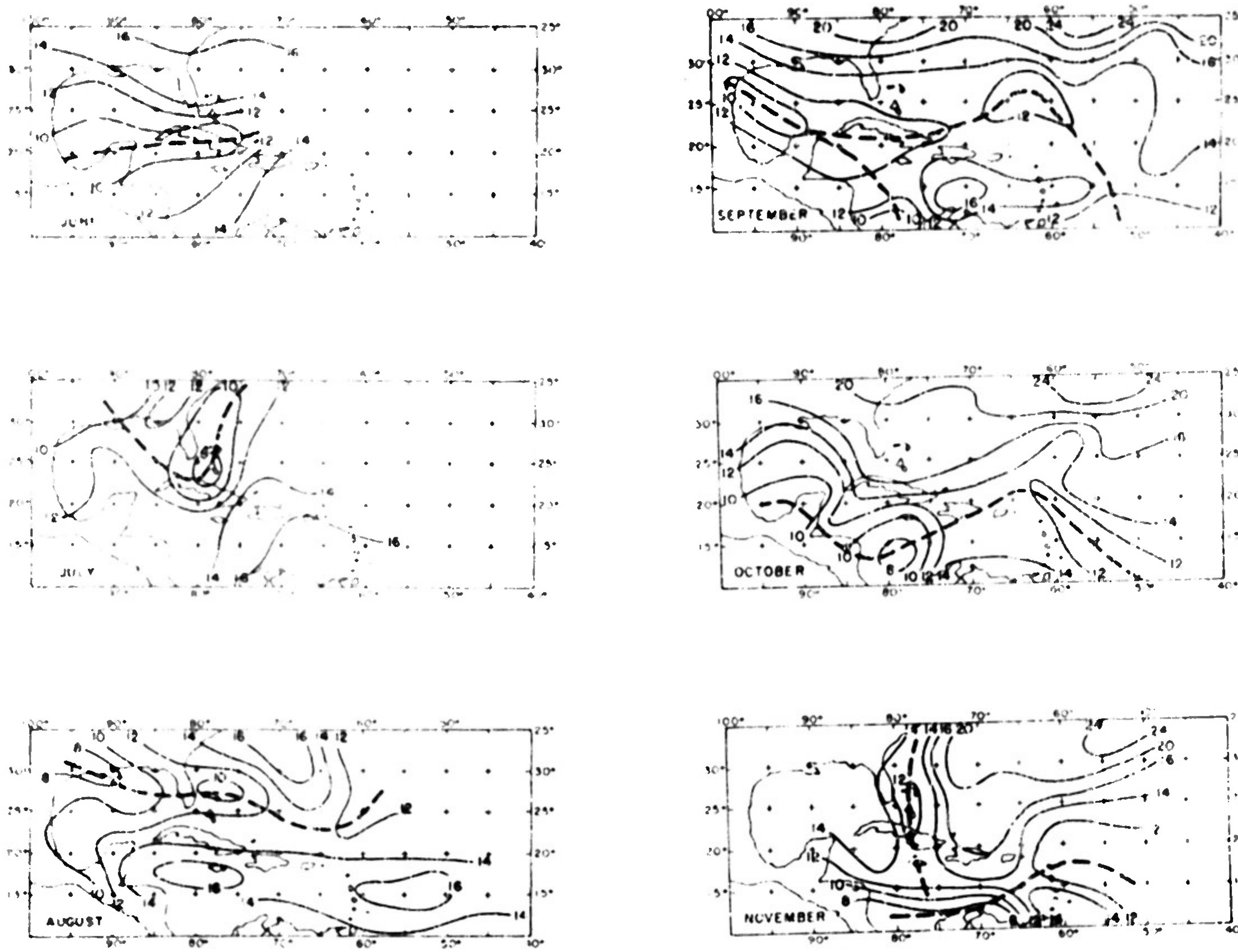


Fig. 10. Median speed of motion (mph). Heavy dashed line shows axis of slowest median speed.

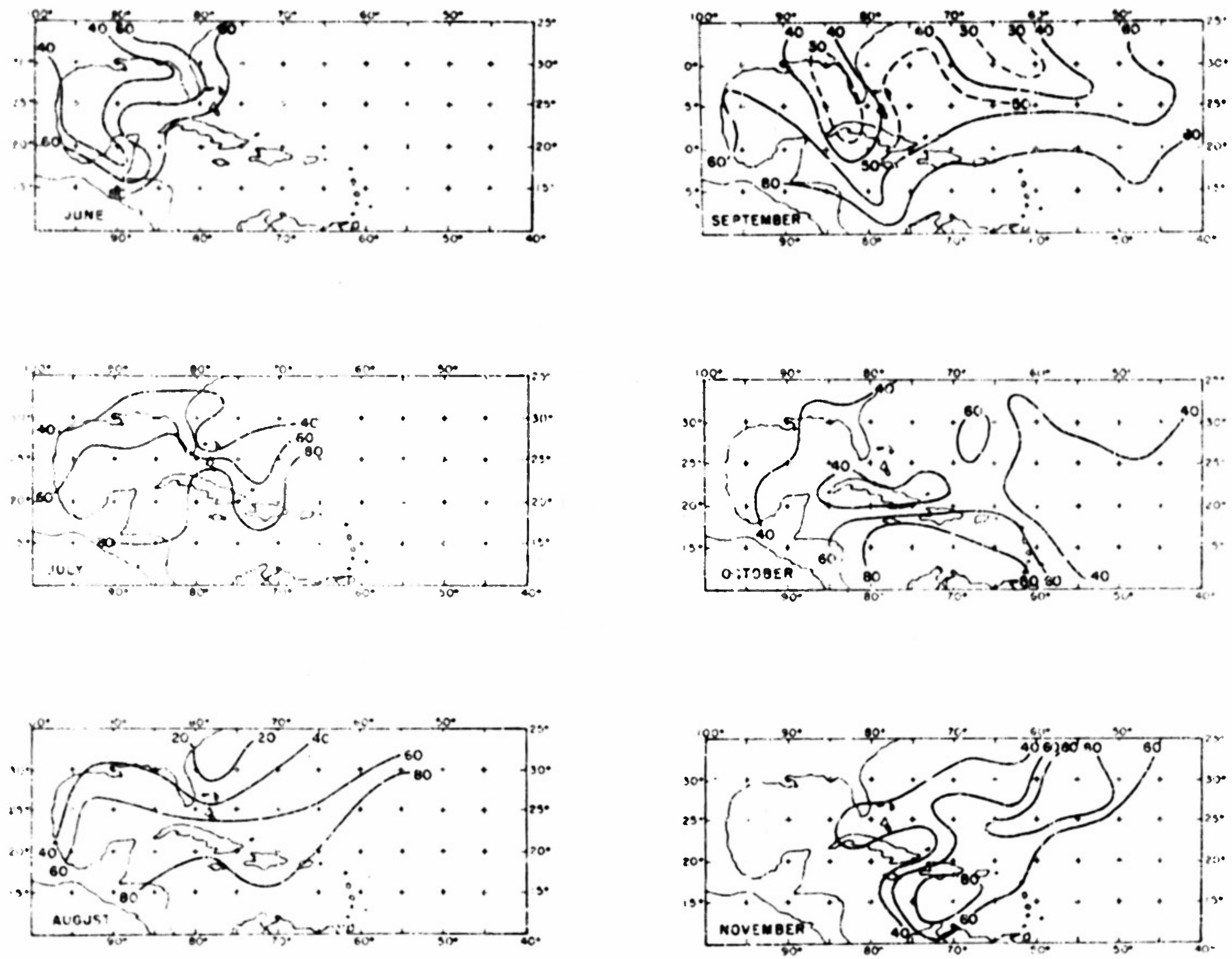


Fig. 11: Percentage frequency of storms moving on a persistent track.

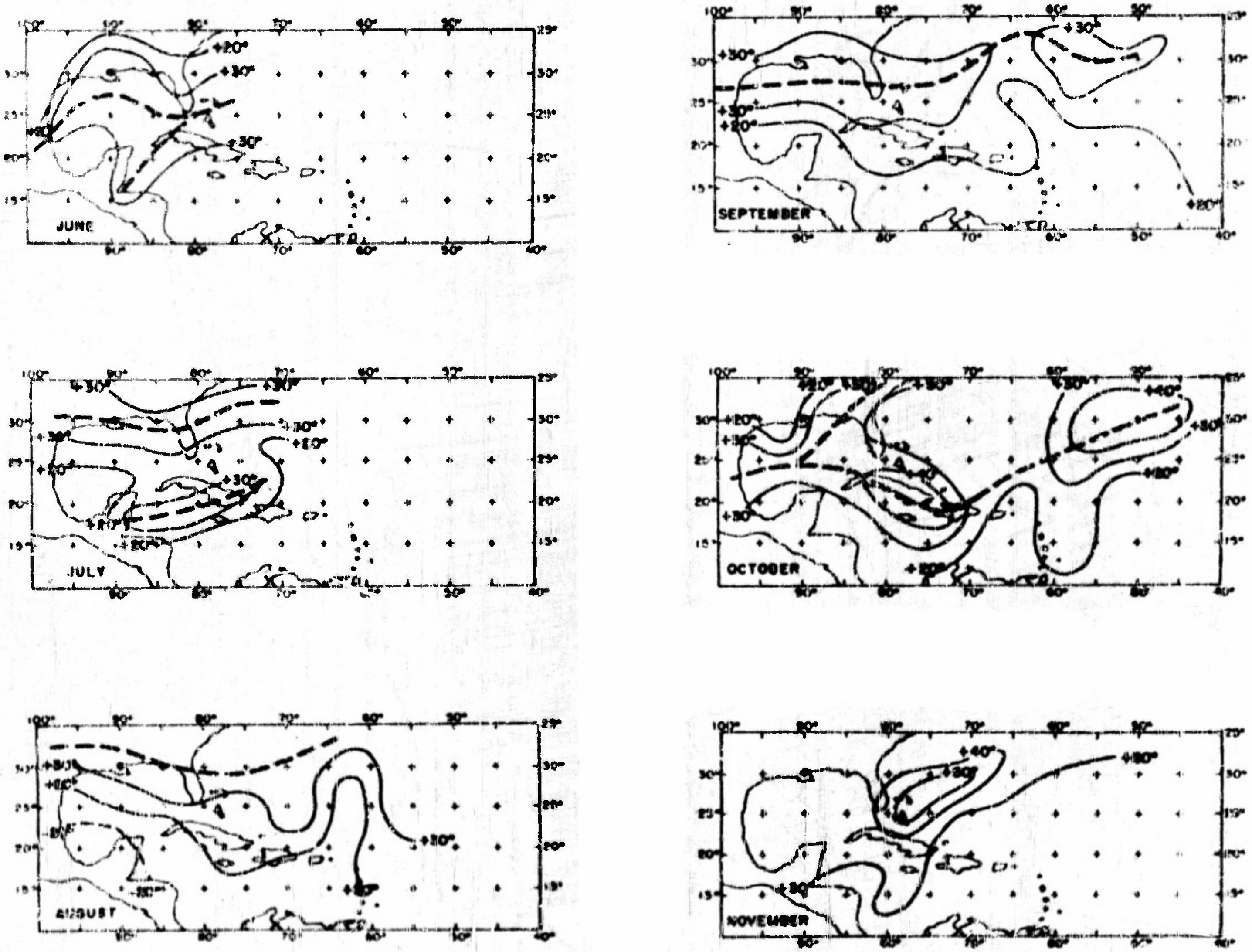


Fig. 12: Median angle of change in direction of motion of nonpersistent storms. Heavy dashed lines indicate axes of largest median angle.